ENERGY OF HARD, SOFT, AND NUCLEONIC COMPONENTS OF EXTENSIVE AIR SHOWER USING DEASA ARRAY

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ABSTRACT

An extensive air shower is generated when a highly energetic cosmic ray enters the atmosphere resulting in soft, hard, and nucleonic components, which a mini array can measure. These studies have been done by Stockholm Educational Air Shower Array (SEASA) located at Sweden, which have 3 detectors per station observing temperature dependence with count rate. Similarly, School Cosmic Rays Outreach Detector (SCROD) located at Boston used educational array of 3 detectors per station to study the G.Z. cutoff. A similar experiment is being set up at Dayalbagh Educational Institute (DEI), Agra in which a mini array consisting of 8 plastic scintillation detectors having dimensions (100 x 100 x 2) cm^3 separated by 8 m at 171 m above sea level. This simulation involves the study of energy deposition of hadrons, γ and lighter leptons (μ^+, μ^-, e^-, e^+) in extensive air shower using CERN based open simulation toolkit GEANT4. The energy range of secondary particles is 0.05 GeV $\leq E_p \leq$ 100 GeV, 10 MeV $\leq E_\gamma \leq 10^4$ MeV, 10^{-3} GeV $\leq E_e^- \leq$ 10 GeV, 10 MeV $\leq E_{e+} \leq 10^4$ MeV, 20 GeV $\leq E_\mu^- \leq$ 7000 GeV, 40 GeV $\leq E_{\pi\pm} \leq$ 7000 GeV. The aim is to observe real life physics and carry out future studies of EAS based on mini array.

KEYWORDS

***Cosmic** ray, extensive air shower, Geant4, CORSIKA*

1. INTRODUCTION

This is known from very early that there are radiations (α-rays, β- rays and γ-rays) which are present in our atmosphere with energies in the range of few 100 keV to MeV. French physicist Augustine De Coulomb found that different kind of radiation is present in the atmosphere which is more energetic than α-rays, β- rays and γ-rays [1] which were discovered by a balloon experiment in which Victor Hess verified presence of this radiation [1]. The energy of these radiation increases as altitude increases. These radiations are coming from outside the earth so named as cosmic rays. Cosmic rays are not actually rays but these are high energetic particles. Various experiments have been done to study composition, energy, and the sources of these cosmic rays. Clay showed geomagnetic dependence of cosmic rays which indicates that cosmic rays consist of charged particles [2]. Balloon experiment observed high flux of particles in the energy range 10^{-2} GeV to 10^{-1} GeV. On 28 February and 7 March 1942 two cosmic ray bursts were recorded on earth and the sun was identified as a source with particles having energy up to 10^{10} eV calling them solar cosmic rays (SCRs). Galactic cosmic rays (GCRs) were discovered with the help of TIGER (Trans-Iron Galactic Element Recorder) experiment which had been set up in Antarctica. The TIGER instrument measures elemental composition of cosmic rays heavier than iron [3]. From the experimental data, it is found that the cosmic rays lying in the energy range of 10^{11} to 10^{14} eV, were expected to come from galactic sources. The cosmic rays coming from outside the galaxy are termed extragalactic cosmic rays and are expected to have energy $\geq 10^{15}$ eV. The cosmic rays whose sources are not yet defined are termed as anomalous cosmic rays.

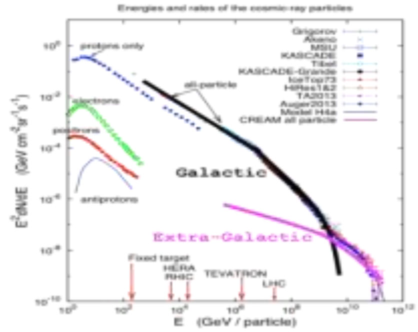


Figure 1. cosmic ray energy spectrum having energy of primaries at abscissa and flux of particles at ordinate [4].

In the cosmic ray spectrum shown in Fig. 1, two kinks are present called knee and ankle based on change in slope of flux at these two separate points. Before the knee region the flux of particles is observed to as 1 particle/m^2 -second. The flux of particles between ankle and knee has been observed to be as 1 particle/km^2-sec. After the ankle region the flux reduces to 1 particle/km^2-year.

1.1. AIR SHOWER

Over the last 104 year, physicists have been studying cosmic rays using earth's atmosphere as a detection technique. The phenomenon happens when a high energetic cosmic ray (referred to as primary) like proton or any other heavy nuclei interact with the air molecules present in the atmosphere, it initiates a cascade of particles (referred to as secondaries) which is known as Extensive Air Shower (EAS). Cascade is chain of particles where every particle produces or decays to the next in line based on mass. EAS produce three components when interact with earth's atmosphere. These components are electron-photon component (e^-, e^+, γ), hadronic components ($\pi\pm$, kaons) and muonic components ($\mu\pm$) which are also known as soft, nucleonic and hard components respectively. The formation of EAS is shown in Fig. 2 [5].

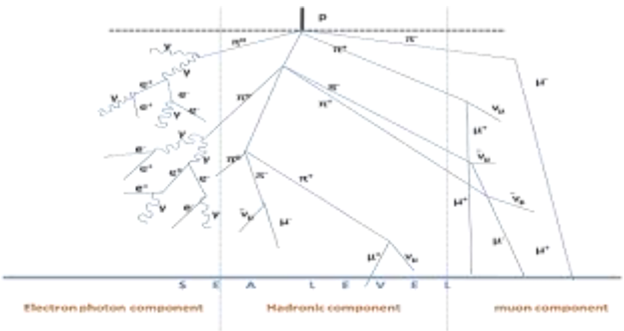


Figure 2. Formation of Extensive air shower

$$\pi^0 \rightarrow 2\gamma;\ \pi^+ \rightarrow \mu^+ + \nu_\mu;\ \pi^- \rightarrow \mu^- + \nu_\mu$$

As shown in figure 2 the shower divides into three parts

(a) electromagnetic cascade (mainly electrons, gammas, and positrons)
(b) hadronic cascade (mainly muon, pions, kaons)
(c) Nucleonic cascade (ν_e, ν_μ.)

In first collision, more than 50 secondaries are produced, in which most of them are pi mesons collectively known as pions. Charged pions are relatively long lived as compared to neutral pions so, they interact with other nuclei to form cascade of particles and this process is known as hadronic shower. Neutral pions are short lived, so they decay into two gammas before interacting with nuclei. These photons further interact with nuclei in the air to produce electromagnetic shower. Generally, both types of showers are collectively known as Extensive Air Shower. EAS was observed by French physicist Pierre Victor Auger in 1930.When EAS develops into atmosphere, it produces more and more secondary particles. A fraction of kinetic energy of primary particle gets converted into mass energy and then remaining kinetic energy is distributed among shower secondaries. This continues till average energy of shower particle is unable to produce further secondary particles and this point is known as shower maximum.A high energy proton interacts with earth's atmosphere resulting in multiple high energy mesons produced via elastic collision. The interaction length of all secondaries is not equal and depends on the particle itself.Cosmic ray air shower can be described by mainly three variables, the atmospheric depth of the first interaction X_o , total number of electromagnetic particles N_e and the total number of muon N_μ . X_{max} (the atmospheric depth at which the shower size is maximum) is the important parameter for shower detection and can be related to reconstruction of shower parameters shown in Figure 3.

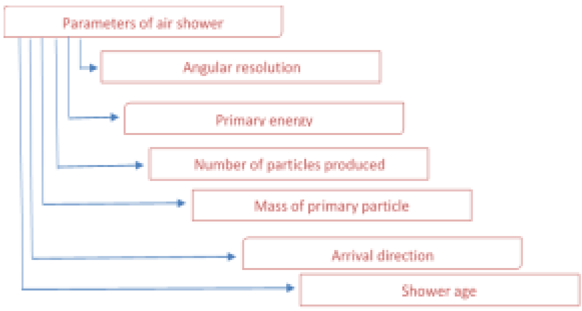


Figure 3

A fraction of kinetic energy of primary cosmic ray converted into mass energy of secondaries and continues until critical energy is reached. Heitler gave a toy model for the better understanding of EAS produced in the atmosphere. He assumed that shower consists of only one type of particles and after each interaction at a certain distance it splits into two new particles of energy half of the initial energy. As the distance increases as nR, energy of particles decreases as $E/2^n$ whereas the number of particles increases as 2^n. The number of electrons and positrons are 2/3 and number of photons are 1/3. In the toy model shown in Fig.4, a photon is acting as a primary particle having primary energy as E. After the interaction with the earth's atmosphere, it undergoes pair production and gives equal amount of energy to electron and positron and this process will continues till critical energy reaches [6]. Beyond 10^{14} eV, it is difficult to detect cosmic rays with balloon experiment, so ground arrays are required for their detection. Linsley suggested a low-cost detection method for cosmic rays which comprises of few closely packed detectors called a mini array [7]. These mini arrays help to explore the information about the primary particle [8-9]. Several mini arrays have been set up like SCROD (School Cosmic Ray Outreach Detector) at Boston, SEASA (Stockholm Extensive Air Shower Array) at Sweden to study air showers. SCROD has 3 detectors per station with the help of which they studied the GZ cut-off [10]. Similarly, SEASA focuses on various studies of EAS like temperature dependence and pressure dependence with count rate [11]. The mini array can measure the arrival time of the particles and the total energy deposited by these particles in detector.

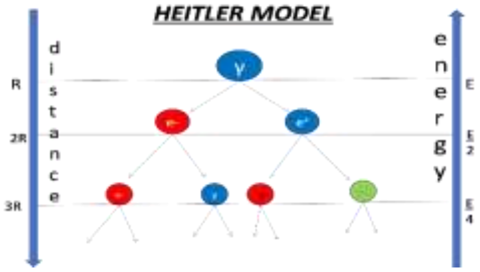


Figure 4

1.2. DEASA

DEASA stands for Dayalbagh Educational Air Shower Array. It is a mini array which is being set up in Dayalbagh Educational Institute, Agra. The array comprises of eight plastic scintillator detectors having dimension 100 x 100 x 2 $cm^3$with the separation 8m from each other. The fabrication, photomultiplier tubes calibration, light leakage tests have been completed on all detectors. The aim of this array is to study the properties of air shower with signal electronics and data acquisition. Under the initiative of TIFR, Mumbai, it is an attempt to study the properties of EAS which is at 171 m above the sea level. The layout of DEASA is given below in the Fig.5.

Figure 5. overview of DEASA

2. Energy Deposition

When radiation interacts with matter via electromagnetic and weak interactions, different processes like Bremmstrahlung, ionization loss, nuclear reactions, scattering and collision take places [12]. The sum of energy loss in all these processes is equal to the total energy of the incident particle. Energy deposition is the amount of energy deposited by incident particles in detector. Bohr gives the approximation formula for deposited energy using classical arguments and later this formula proposed by Bethe-Bloch using quantum mechanics which is given by [12]

$$-\frac{dE}{dX} = \xi\left\{\ln(\frac{2m_e C^2\beta^2\gamma^2}{I}) + \ln\left(\frac{\xi}{I}\right) + 0.2 - \beta^2 - \delta(\beta\gamma)\right\}$$

$$\xi = 2\Pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A}\frac{1}{\beta^2} x\rho$$

with
$2\pi N_A r_e^2 m_e c^2 = 0.1535$ $MeVcm^2/g$

Where,
$N_A=6.02*10^{23}$
I = mean excitation potential, Z=atomic number of absorbing materials, A = atomic mass of absorbing material.

In this paper the air shower has been simulated in CORSIKA (Cosmic Ray SImulation for KAscade) for the specifications of Agra then these particles generated at ground level are thrown on the plastic scintillation detectors. The detectors have been spread on the ground level with specific hit regions corresponding to the area and position of the detectors. Data has been analyzed from the hits in them.

2.1. MONTE CARLO SIMULATIONS

Monte Carlo simulation gives the probability of all possible outcomes for a certain problem. When a model has uncertain parameters then Monte Carlo is required to analyze them. It is used in different fields such as physical science, high energy physics, statistics, and various other fields. It is always indeterministic, in other words it gives the approximation of reality. Various open software like CORSIKA and Geant4 are based on Monte Carlo method.

CORSIKA stands for Cosmic Ray SImulation for KAscade. It is a simulation program for KASCADE experiment for the studies of extensive air shower. KASCADE is an experimental setup at Karlsruhe, Germany for the study of primary composition of cosmic rays in the energy range 10^{13} to 10^{20} eV [13]. The input file contains information about energy, type, location and direction of incident particle. CORSIKA performs different task such as transporting and tracking of particles within or without the presence of magnetic field of earth. Output files are generated in.txt, tat, .info and other formats. Information about particles and simulation run can be extracted from these output files [14]. Output files gives information about the secondaries produced by that primary cosmic ray. It gives longitudinal and latitudinal parameters of shower development by which studies of particle distribution and energy deposition by particles at various depths can be done.

Geant4 is open software provided by CERN used for simulating the transition of particles through matter. It includes a complete range of functionality [15]. Geant4 is being used in various other fields like medical (dose deposition is calculated by treating a target as a patient), high energy physics (information about the primary can be extracted), nuclear and particle accelerator, space and radiation. It is a full set of libraries written in C++ language which allows user to simulate the detector system. After specifying the geometry of detector, it transports particles shot into detector by simulating the interaction of particle with matter based on Monte Carlo simulation. It includes a complete range of functions like geometry, tracking, physics list (like electromagnetic and hadronic process), primary generator action, event manager action and various other functions. In primary generator class information about the primary particle is defined. It includes information about number of particles, particle type, and particle energy.

In detector construction class, various shapes of detector can be defined. With the help of detector construction class, a detector having dimensions (100*100*2) cm^3 of polystyrene material is constructed in Fig6 (a). With the help of primary generator class, secondary particles produced in an EAS such as electron and positron having energy in the range of few100 MeV to 1GeV has been set as primary particle and allow it to incident on the detector to find out the total energy deposited by the primary particle in the detector in Fig6(b). This is being done with the help of predefined program in Geant4 **TestEm18,** one of the extended examples in which electromagnetic physics process is already defined based on the Geant4 Standard electromagnetic model. The electromagnetic physics is built through the G4EmStandardPhysics constructer class. In these standard electromagnetic models initiate several processes for each particle which cover the physics from 0-100 TeV for gamma, e^-, e^+, and till 1 PeV for muons.

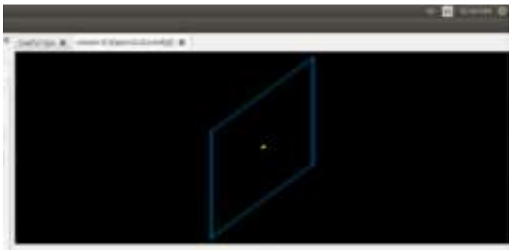


Figure 6(a) detector in simulation

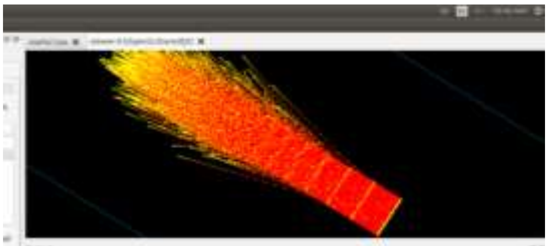
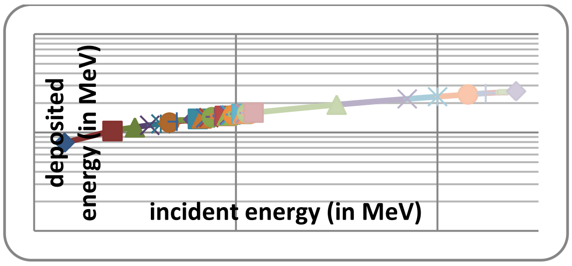


Figure 6(b) beam of 1000 electron in simulation

3. Results and Discussion

Taking electron and muons as the incident particle, graphs have been plotted as in Figure7 and Figure 8 for energy deposition by the secondary particles in detector for a given incident energy. As shown in these figures' total energy loss and energy deposition increased linearly with the increase in energy of incident particles. Fig7 (a) illustrate analytical results for energy deposition of electrons in polystyrene which is confirmed by the results for iron. [6]. Fig.7 (b) is the graph for E > 100MeV electron which deposit 2-2.5 MeV cm^{-2} g^{-1} energy in a detector. Results suggest that a 1 GeV electron can traverse 1cm of polystyrene by depositing 2.12 MeV energy. Fig.8 (a) illustrates analytical results for energy deposition of muon in polystyrene which is confirmed by the results for iron. Fig.8 (b) indicates graph for E > 100MeV, 20 keV energy per cm^2 is deposited by negative muon in detector.

The energy of the particle deposited in the detector is solved analytically by the Bethe Bloch equation for relativistic incident secondaries in Matlab. These same particles were incident on the simulated detector in Geant4 program. In this work, the case of the two leptons with different energy could be studied and plotted. The energy range defined for these leptons does not consider the whole range of energies. In this work, simulations have been done for leptons of high energies using Standard electromagnetic model. The future work is to define the model in the TestEm 18 program for low energetic hadrons



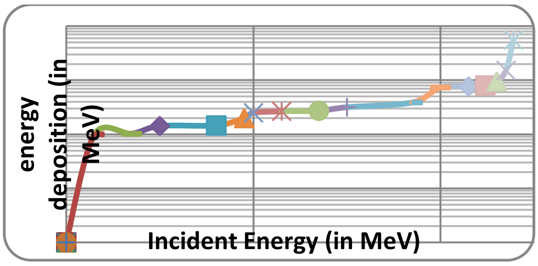
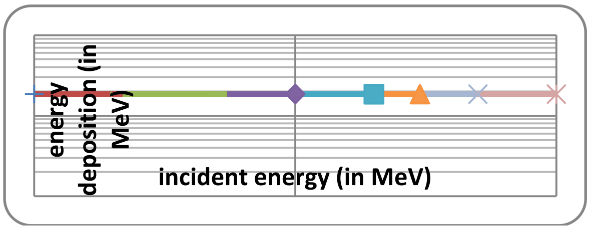


Figure 7(a) **Figure 7(b)**

Energy deposition of electron in polystyrene as a function of incident energy (a) theoretical results calculated by Bethe Bloch Formula (b) simulation results.



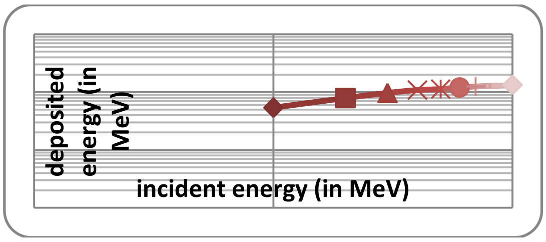


Figure 8(a) **Figure 8(b)**

Energy deposition (in MeV) of muon in polystyrene as a function of incident energy (in MeV) (a) theoretical results calculated by Bethe Bloch Formula (b) simulation results.

The preliminary studies of the detectors in DEASA have started. To familiarize with the potential of air shower array, this simulation exercise is performed in geant4.10.2.

4. Conclusions

The DEASA array is set up in Faculty of Science with an aim to develop an instrument to observe showers of secondary particles along with temperature and pressure studies. This data will be analyzed to study the effects of climate change and solar disturbances. Many researchers have connected the effects of cosmic rays with atmospheric physical-chemical phenomena. Over the years many instruments and new techniques have been defined to study cosmic ray variations. To advance this space research program such arrays can study cosmic ray flux variations with time and their relationship with different atmospheric processes. The short and long-term variations in cosmic ray muon flux can also be observed with such arrays to better out atmospheric studies. The high energy field has applications in astrophysics, medical physics, space physics and muon tomography [16].

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